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Gaska et al.

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(54) **DEEP ULTRAVIOLET LIGHT EMITTING DIODE**

(71) Applicant: **Sensor Electronic Technology, Inc.**, Columbia, SC (US)

(72) Inventors: **Remigijus Gaska**, Columbia, SC (US); **Maxim S. Shatalov**, Columbia, SC (US); **Michael Shur**, Latham, NY (US); **Alexander Dobrinsky**, Loudonville, NY (US)

(73) Assignee: **Sensor Electronic Technology, Inc.**, Columbia, SC (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

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(22) Filed: **Nov. 9, 2015**

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US 2016/0064601 A1 Mar. 3, 2016

Related U.S. Application Data

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H01L 33/06 (2010.01)
H01L 33/32 (2010.01)

(Continued)

(52) **U.S. Cl.**
CPC ***H01L 33/06*** (2013.01); ***G06F 17/5068*** (2013.01); ***H01L 33/0025*** (2013.01);

(Continued)

(58) **Field of Classification Search**
CPC . H01L 33/06; H01L 33/0025; H01L 33/145; H01L 33/10; H01L 33/46; H01L 33/38; H01L 33/32; H01L 33/04; H01L 33/0075; G06F 17/5068

See application file for complete search history.

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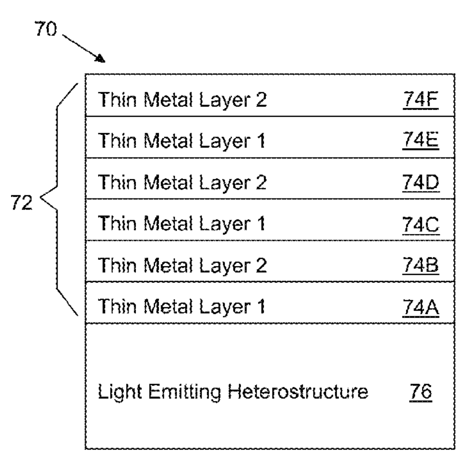
Primary Examiner — Roy Potter
(74) *Attorney, Agent, or Firm* — LaBatt, LLC

(57) **ABSTRACT**

A method of fabricating a light emitting diode, which includes an n-type contact layer and a light generating structure adjacent to the n-type contact layer, is provided. The light generating structure includes a set of quantum wells. The contact layer and light generating structure can be configured so that a difference between an energy of the n-type contact layer and an electron ground state energy of a quantum well is greater than an energy of a polar optical phonon in a material of the light generating structure. Additionally, the light generating structure can be configured so that its width is comparable to a mean free path for emission of a polar optical phonon by an electron injected into the light generating structure.

20 Claims, 13 Drawing Sheets



Related U.S. Application Data

continuation-in-part of application No. 13/161,961, filed on Jun. 16, 2011, now Pat. No. 8,907,322.

(60) Provisional application No. 61/610,671, filed on Mar. 14, 2012, provisional application No. 61/356,484, filed on Jun. 18, 2010.

(51) **Int. Cl.**

H01L 33/04	(2010.01)
H01L 33/10	(2010.01)
G06F 17/50	(2006.01)
H01L 33/00	(2010.01)
H01L 33/14	(2010.01)
H01L 33/46	(2010.01)
H01L 33/22	(2010.01)
H01L 33/38	(2010.01)
H01L 33/40	(2010.01)

(52) **U.S. Cl.**

CPC ***H01L33/0075*** (2013.01); ***H01L 33/04*** (2013.01); ***H01L 33/10*** (2013.01); ***H01L 33/145*** (2013.01); ***H01L 33/32*** (2013.01); ***H01L 33/38*** (2013.01); ***H01L 33/46*** (2013.01); *H01L 33/22* (2013.01); *H01L 33/385* (2013.01); *H01L 33/405* (2013.01); *H01L 2933/0058* (2013.01)

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FIG. 1

Prior Art

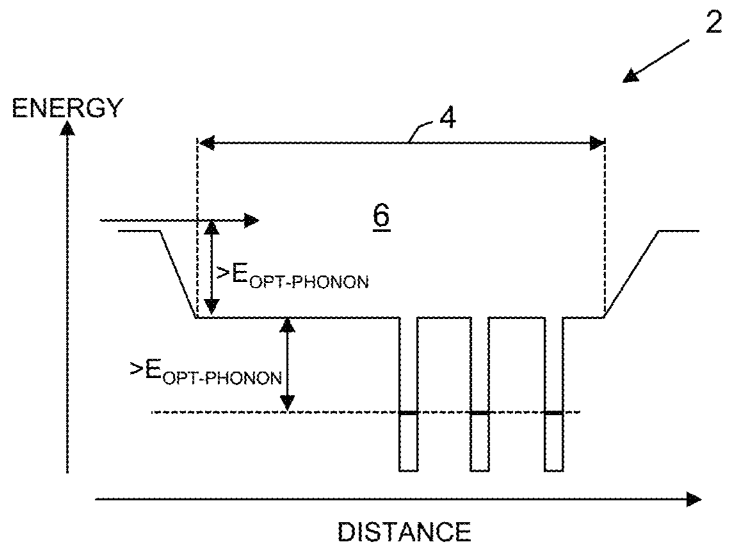


FIG. 2

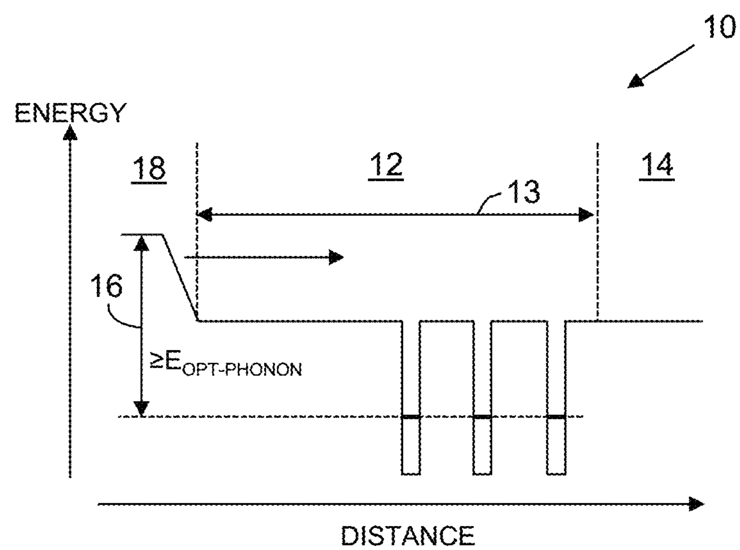


FIG. 3

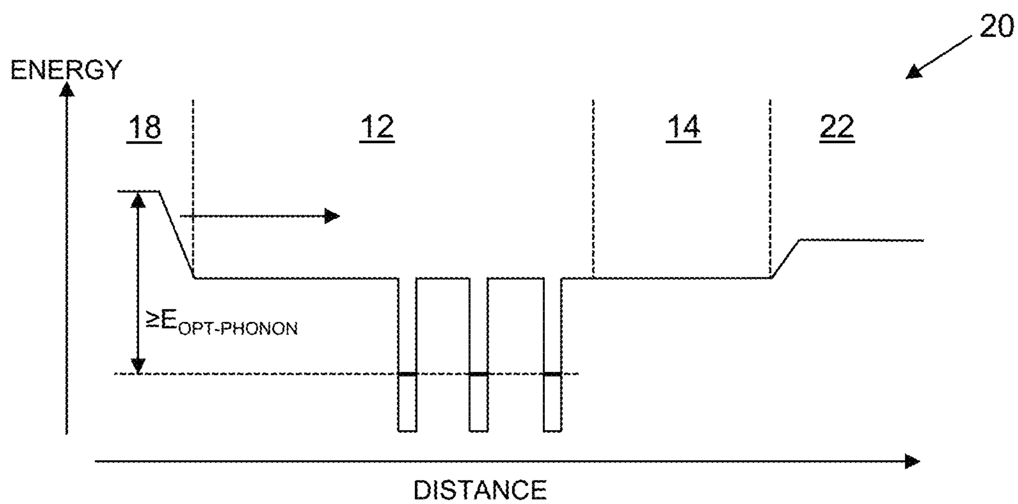


FIG. 4

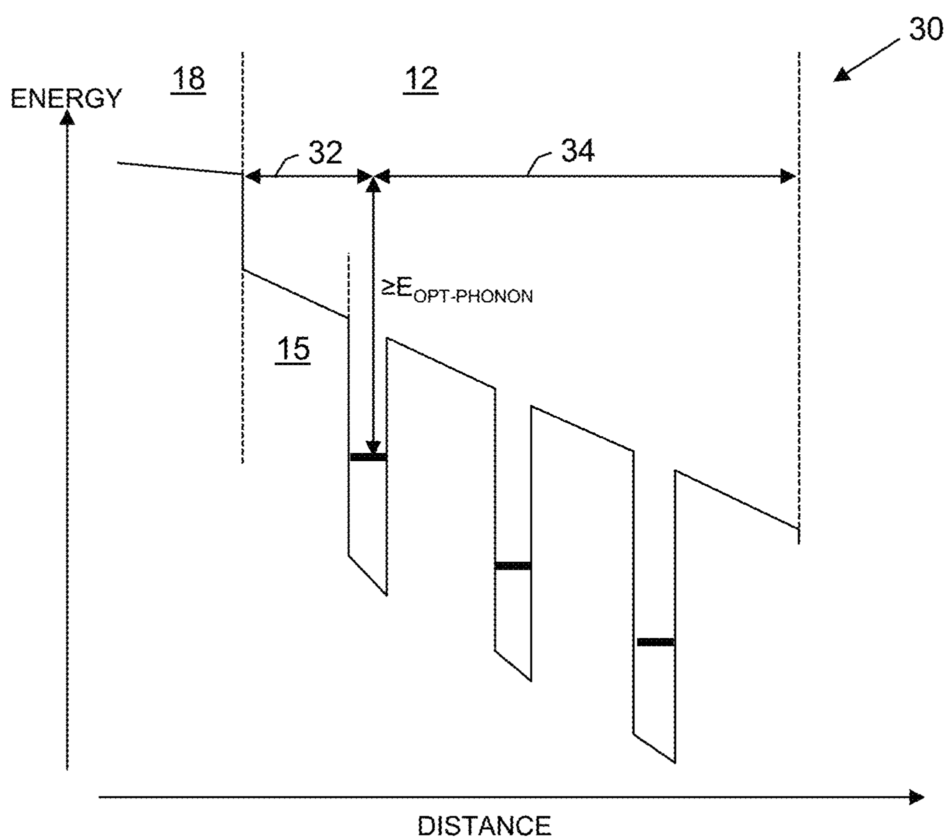


FIG. 5

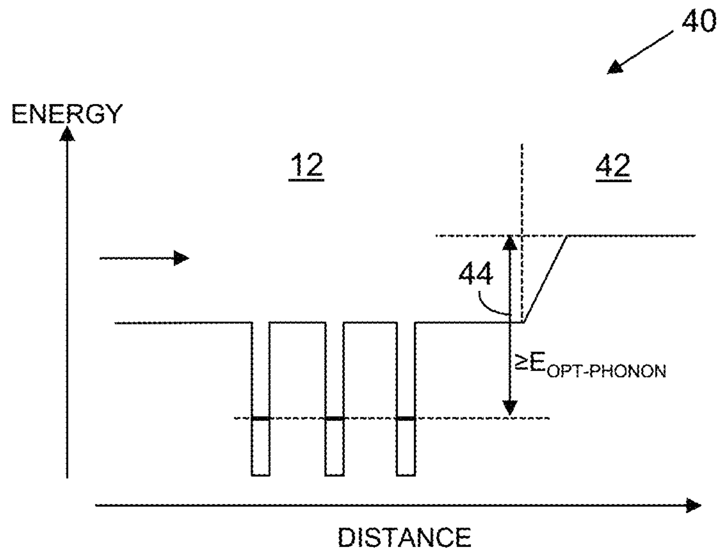

40
ENERGY
12
42
44
≥E OPT-PHONON
DISTANCE

FIG. 6

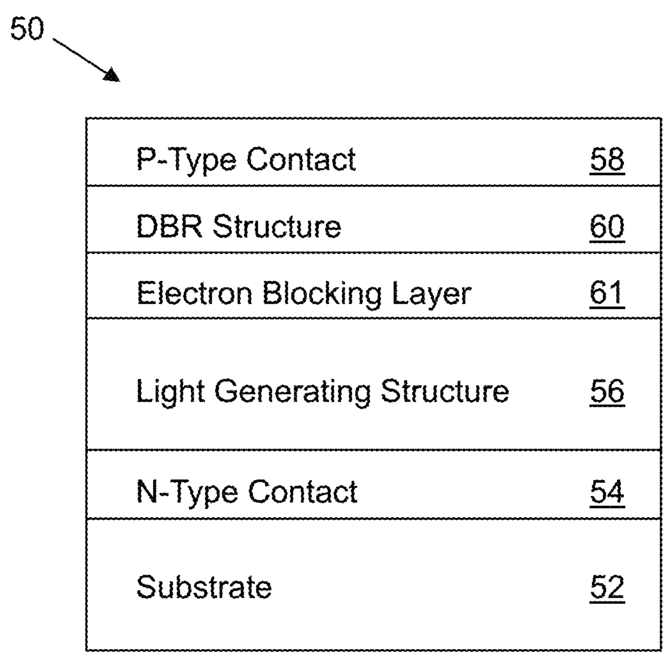

50
P-Type Contact 58
DBR Structure 60
Electron Blocking Layer 61
Light Generating Structure 56
N-Type Contact 54
Substrate 52

FIG. 7

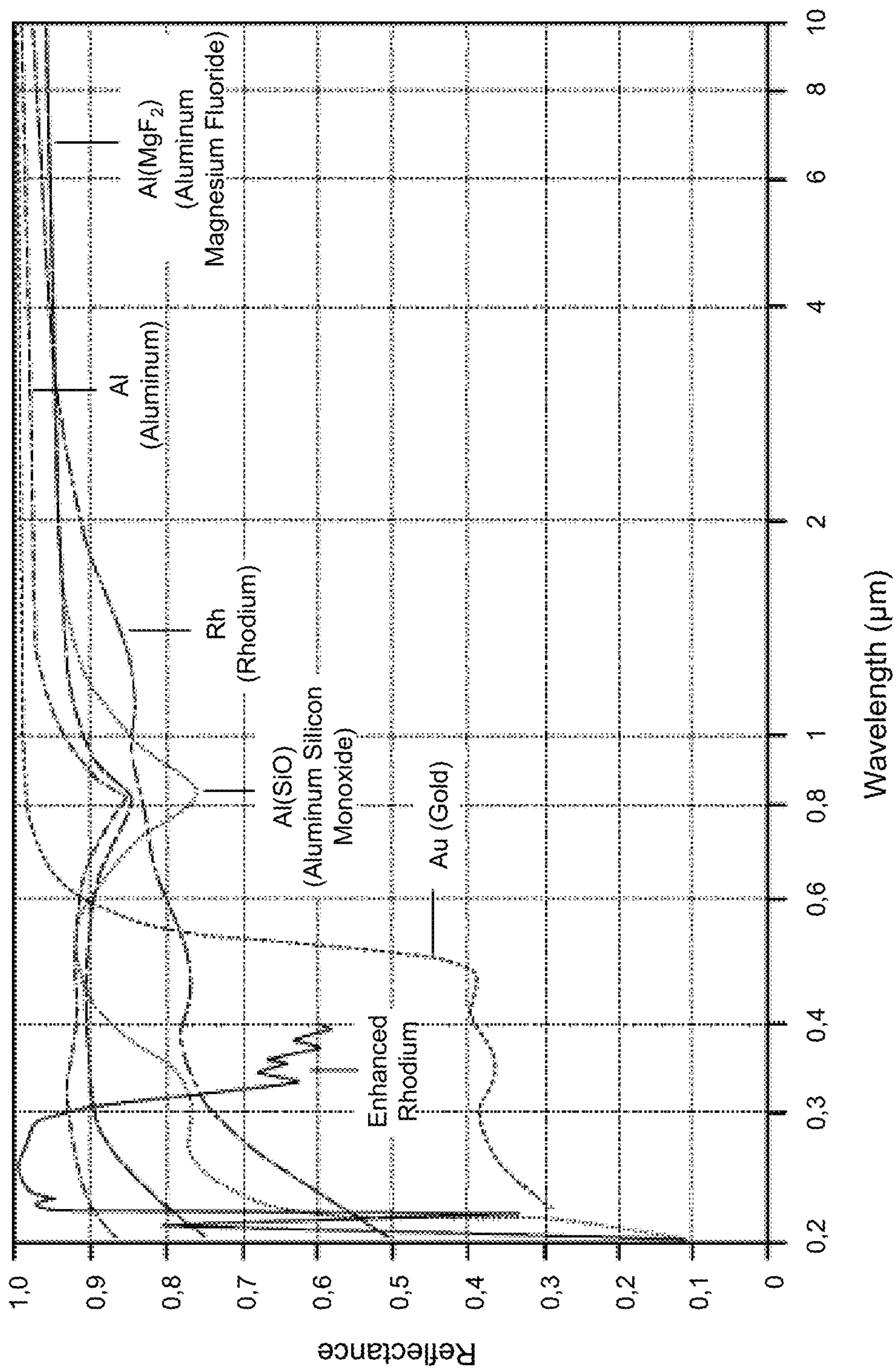

Reflectance
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
Wavelength (μm)
0,2
0,3
0,4
0,6
0,8
1
2
4
6
8
10
Al(MgF2) (Aluminum Magnesium Fluoride)
Al (Aluminum)
Rh (Rhodium)
Al(SiO) (Aluminum Silicon Monoxide)
Au (Gold)
Enhanced Rhodium

FIG. 8A

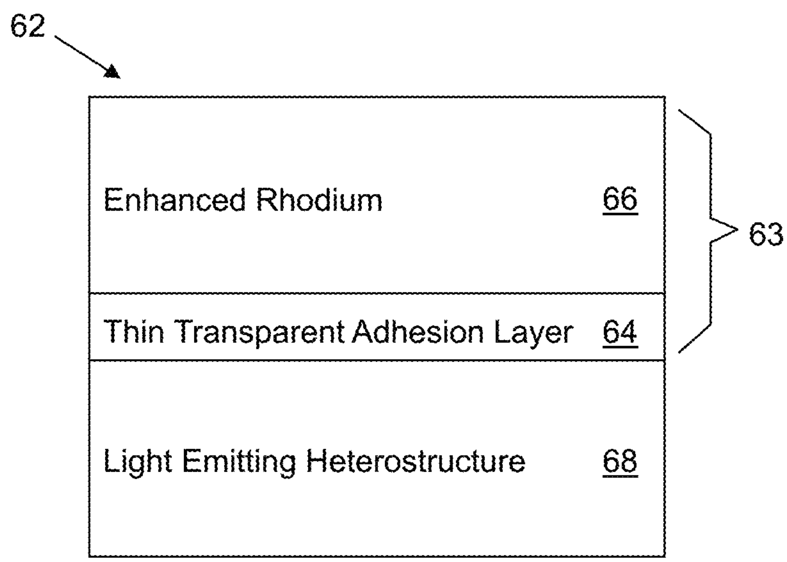

62
Enhanced Rhodium 66
Thin Transparent Adhesion Layer 64
Light Emitting Heterostructure 68
63

FIG. 8B

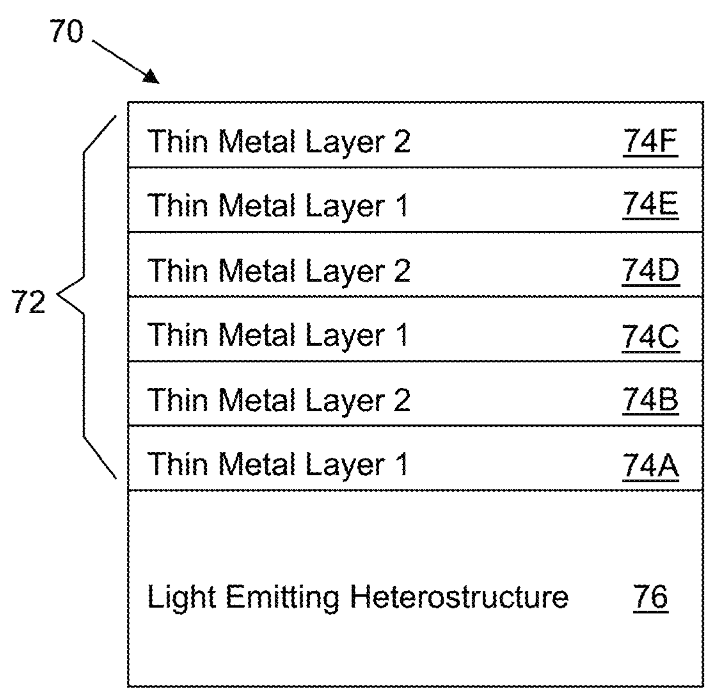

70
Thin Metal Layer 2 74F
Thin Metal Layer 1 74E
Thin Metal Layer 2 74D
Thin Metal Layer 1 74C
Thin Metal Layer 2 74B
Thin Metal Layer 1 74A
Light Emitting Heterostructure 76
72

FIG. 8C

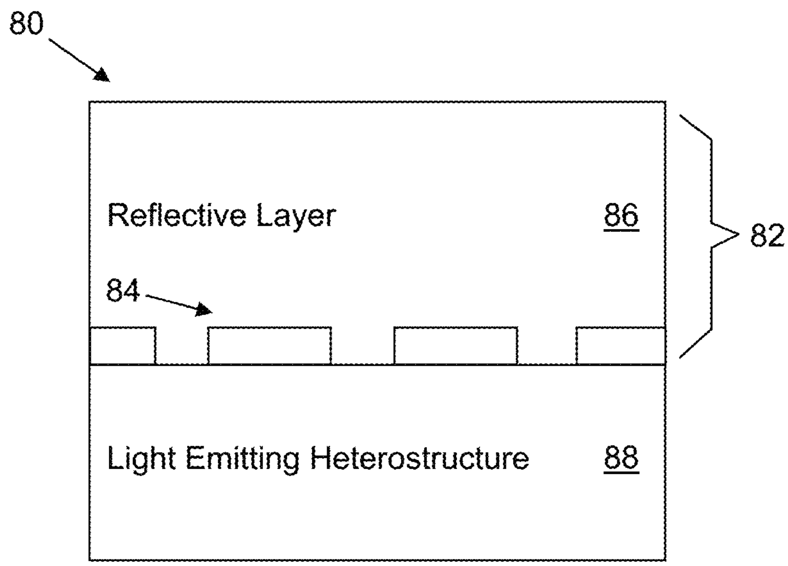

80
Reflective Layer
86
82
84
Light Emitting Heterostructure
88

FIG. 8D

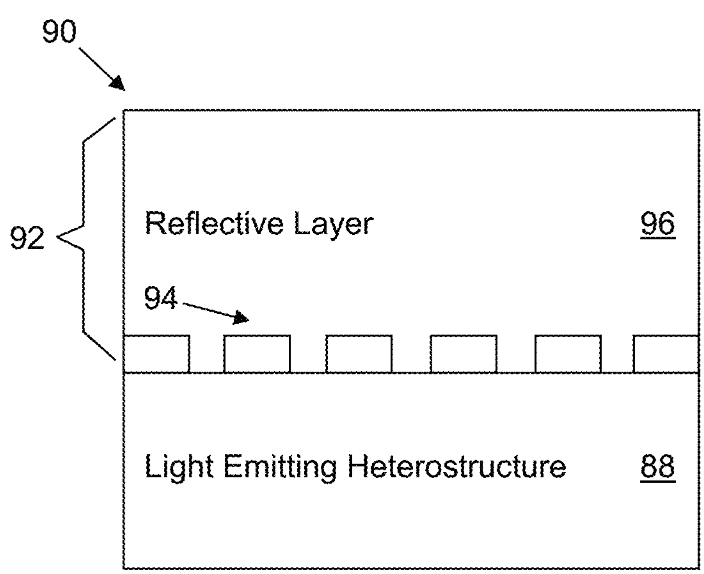
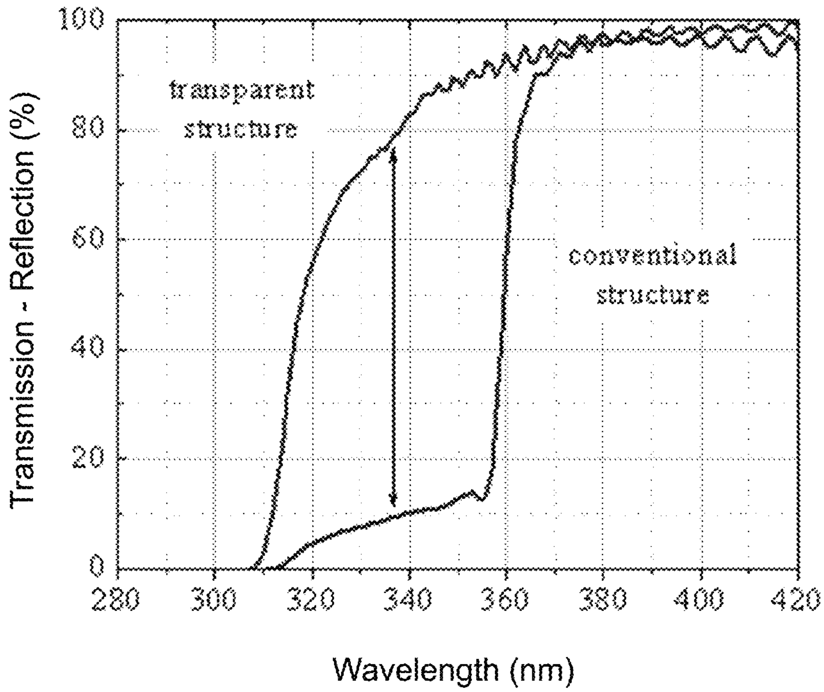

90
Reflective Layer
96
92
94
Light Emitting Heterostructure
88

FIG. 9



100
80
60
40
20
0
280
300
320
340
360
380
400
420
Transmission - Reflection (%)
Wavelength (nm)
transparent structure
conventional structure

FIG. 10

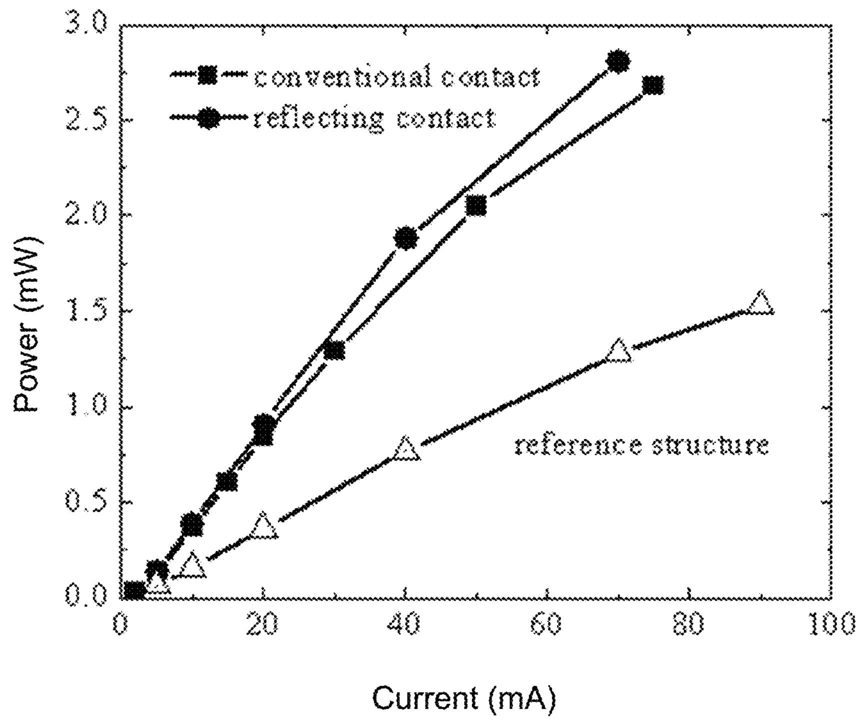

conventional contact
reflecting contact
reference structure
Power (mW)
Current (mA)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
20
40
60
80
100

FIG. 11

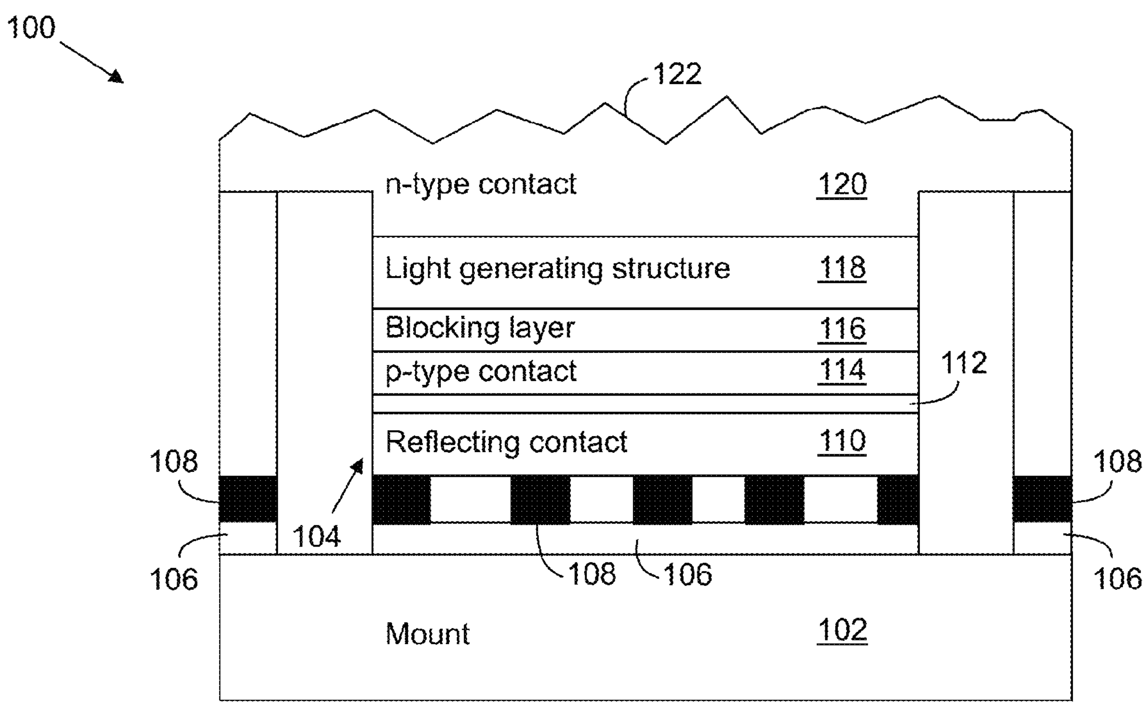

100
122
n-type contact
120
Light generating structure
118
Blocking layer
116
p-type contact
114
112
Reflecting contact
110
108
108
104
108
106
106
106
Mount
102

FIG. 12

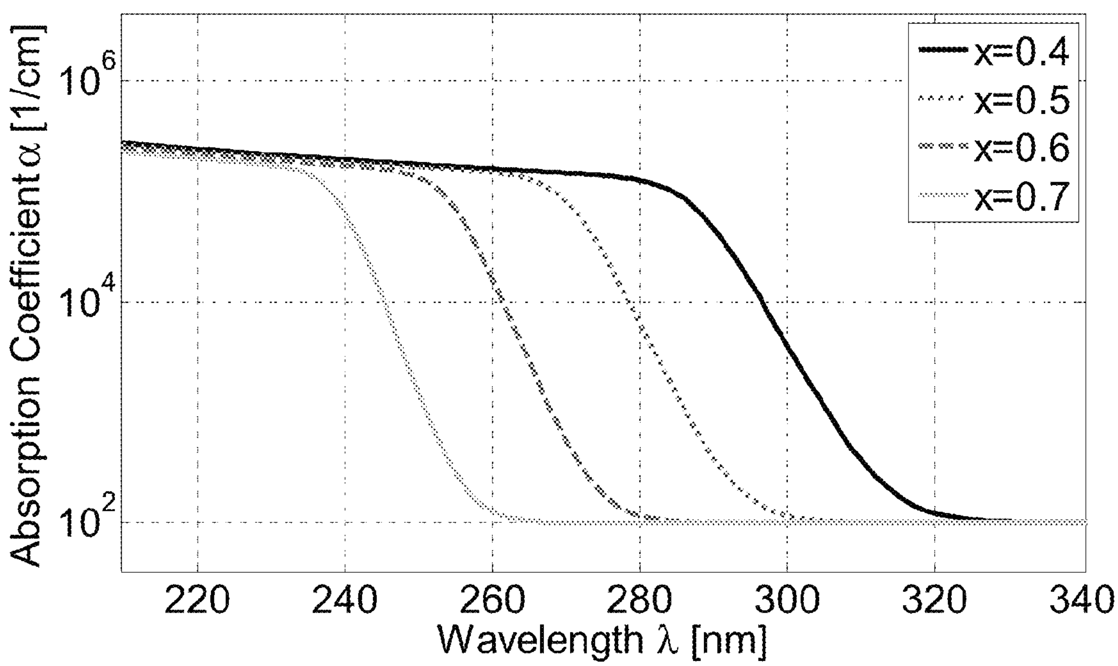
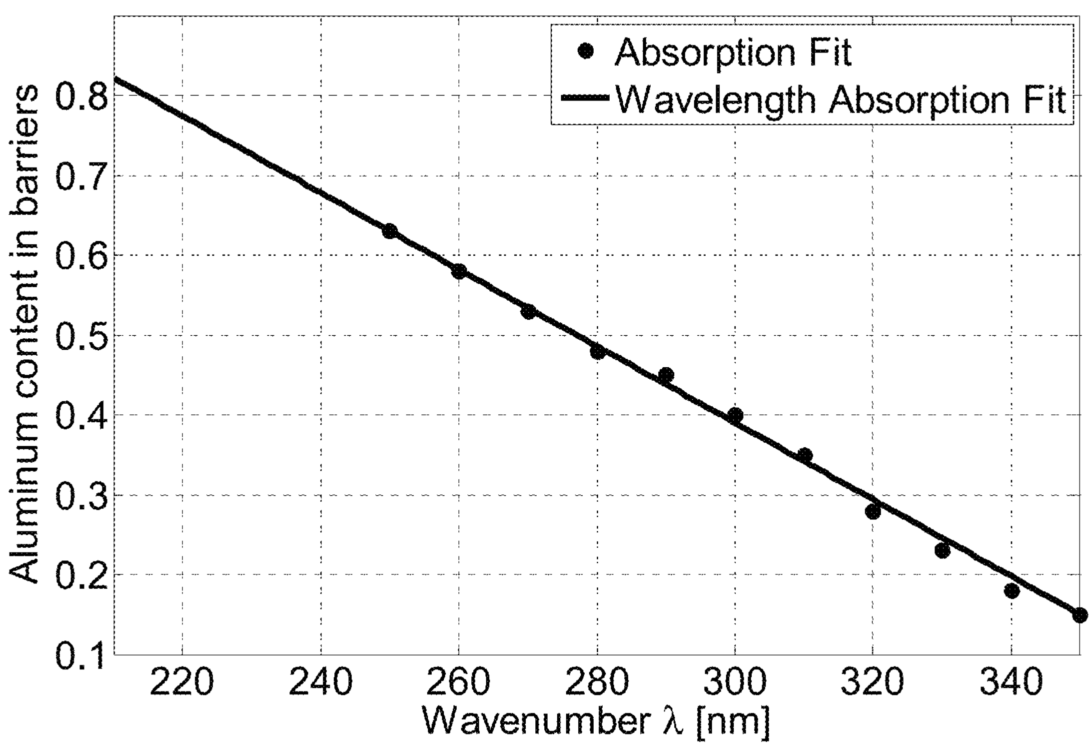
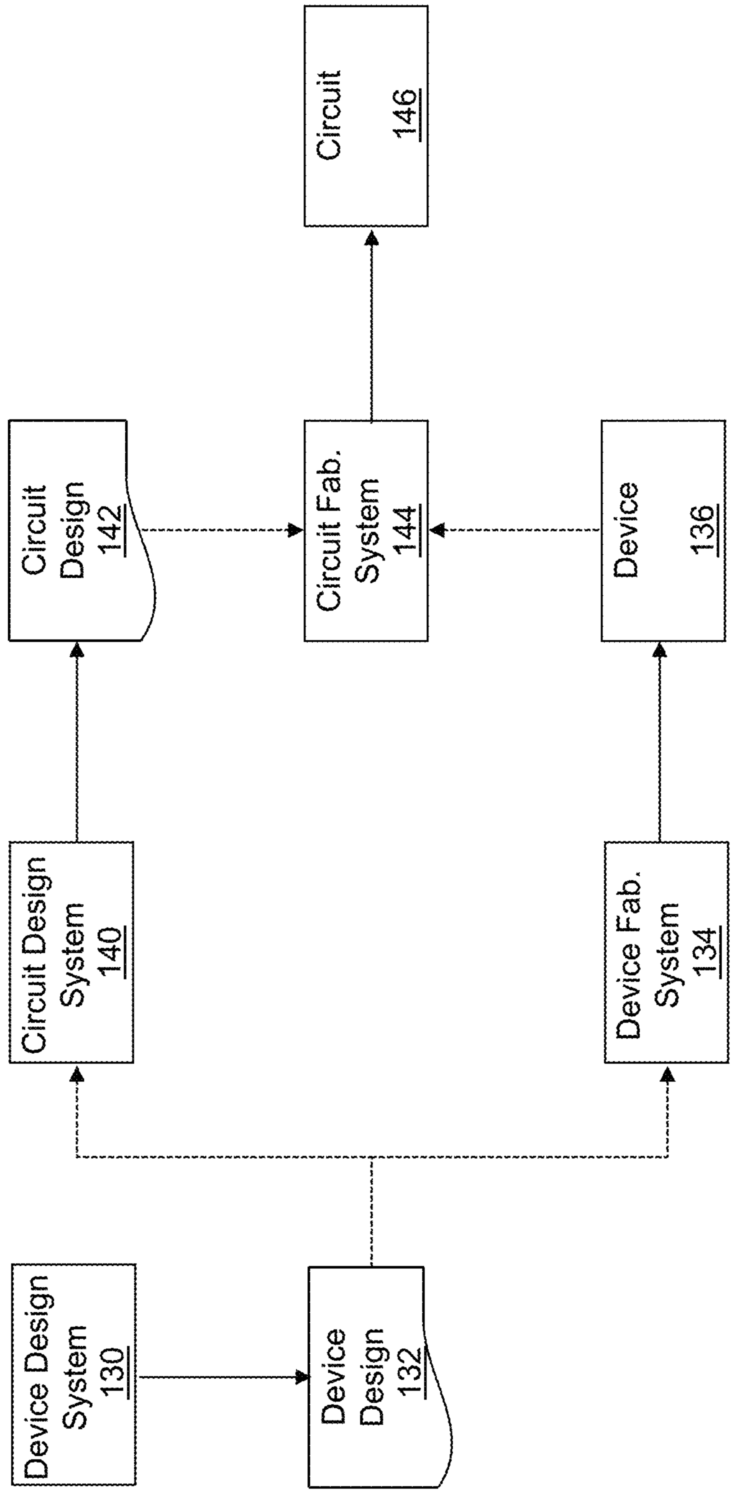

x=0.4
x=0.5
x=0.6
x=0.7
10^6
10^4
10^2
Absorption Coefficient α [1/cm]
220
240
260
280
300
320
340
Wavelength λ [nm]

FIG. 13



Absorption Fit
Wavelength Absorption Fit
Aluminum content in barriers
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
220
240
260
280
300
320
340
Wavenumber λ [nm]

FIG. 14


Device Design System 130
Device Design 132
Circuit Design System 140
Device Fab. System 134
Circuit Design 142
Circuit Fab. System 144
Device 136
Circuit 146

DEEP ULTRAVIOLET LIGHT EMITTING DIODE

REFERENCE TO PRIOR APPLICATIONS

The current application is a continuation of U.S. Utility application Ser. No. 14/514,586, which was filed on 15 Oct. 2014, and which is a continuation of U.S. Utility application Ser. No. 13/803,681, which was filed on 14 Mar. 2013, which claims the benefit of U.S. Provisional Application No. 61/610,671, which was filed on 14 Mar. 2012, and which is a continuation-in-part of U.S. Utility application Ser. No. 13/161,961, which was filed on 16 Jun. 2011, which claims the benefit of U.S. Provisional Application No. 61/356,484, which was filed on 18 Jun. 2010, all of which are hereby incorporated by reference.

GOVERNMENT LICENSE RIGHTS

The U.S. Government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms as provided for by the terms of SBIR Phase II Grant No. IIP-0956746 awarded by the National Science Foundation.

TECHNICAL FIELD

The disclosure relates generally to nitride-based heterostructures, and more particularly, to an improved ultraviolet light emitting nitride-based heterostructure.

BACKGROUND ART

Emerging deep ultraviolet light emitting diodes (DUV LEDs) cover the ultraviolet (UV) range down to 210 nanometers (nm), and provide output powers already sufficient for many applications. Additionally, these devices have high modulation frequencies, low noise, flexible form factor and spectral and space power distribution, high internal quantum efficiency, and a potential to achieve high wall plug efficiency. For example, photoluminescence (PL) studies and ray tracing calculations show that the achieved internal quantum efficiency for a 280 nm DUV LED may be quite high, e.g., between fifteen and seventy percent.

However, external quantum efficiency and wall plug efficiency of typical DUV LEDs is below three percent, with the highest efficiencies for 280 nm LEDs and lower efficiencies for LEDs emitting ultraviolet light having shorter wavelengths. Some reasons for the lower external and wall plug efficiencies include very low light extraction efficiency due to internal reflection from the sapphire substrate and sapphire/air interface, and strong absorption in the top low aluminum (AD-content p-type aluminum gallium nitride (AlGaN) and p-type gallium nitride (GaN) layers. The efficiency of the LEDs is further reduced at higher currents and/or generated powers.

In UV LEDs emitting ultraviolet light having a shorter wavelength, the internal quantum efficiency also drops due to materials problems resulting from growth of AlGaN structures with high Al content. Such growth, among other things, is complicated by the low mobility of Al adatoms, which can result in inhomogeneous Al composition and lateral phase separation, as well as high density of threading dislocations and point defects.

SUMMARY OF THE INVENTION

Aspects of the invention provide a method of fabricating a light emitting diode, which includes an n-type contact layer and a light generating structure adjacent to the n-type contact layer. The light generating structure includes a set of quantum wells. The contact layer and light generating structure can be configured so that a difference between an energy of the n-type contact layer and an electron ground state energy of a quantum well is greater than an energy of a polar optical phonon in a material of the light generating structure. Additionally, the light generating structure can be configured so that its width is comparable to a mean free path for emission of a polar optical phonon by an electron injected into the light generating structure. The diode can include a blocking layer, which is configured so that a difference between an energy of the blocking layer and the electron ground state energy of a quantum well is greater than the energy of the polar optical phonon in the material of the light generating structure. The diode can include a composite contact, including an adhesion layer, which is at least partially transparent to light generated by the light generating structure and a reflecting metal layer configured to reflect at least a portion of the light generated by the light generating structure.

A first aspect of the invention provides a method of fabricating a light emitting heterostructure, the method comprising: creating a design for the light emitting heterostructure based on a set of attributes of a polar optical phonon, wherein the light emitting heterostructure includes an n-type contact layer and a light generating structure including a plurality of quantum wells and having a first side adjacent to the n-type contact layer, and wherein the creating includes: selecting materials for the n-type contact layer and a quantum well in the plurality of quantum wells based on an energy of the polar optical phonon in a material of the light generating structure, wherein a difference between a conduction band edge energy of the n-type contact layer and an electron ground state energy of the quantum well is greater than the energy of the polar optical phonon; and selecting a target width of the light generating structure based on a mean free path for emission of a polar optical phonon by an electron injected into the light generating structure, wherein the target width is comparable to the mean free path; and fabricating the light emitting heterostructure according to the design.

A second aspect of the invention provides a method of fabricating a light emitting heterostructure, the method comprising: creating a design for the light emitting heterostructure based on a set of attributes of a polar optical phonon, wherein the light emitting heterostructure includes an n-type contact layer, a light generating structure including a plurality of quantum wells and having a first side adjacent to the n-type contact layer, and a blocking layer located on a second side of the light generating structure opposite the first side, and wherein the creating includes: selecting materials for the blocking layer and a quantum well in the plurality of quantum wells based on an energy of the polar optical phonon in a material of the light generating structure, wherein a difference between a conduction band edge energy of the blocking layer and an electron ground state energy of the quantum well is greater than the energy of the polar optical phonon; and selecting a target width of the light generating structure based on a mean free path for emission of a polar optical phonon by an electron injected into the light generating structure, wherein the target width is comparable to the mean free path; and fabricating the light emitting heterostructure according to the design.

A third aspect of the invention provides a method of fabricating a light emitting device, the method comprising: forming an n-type contact layer; forming a light generating structure having a first side adjacent to the n-type contact layer, the light generating structure including: a set of quantum wells, wherein a difference between a conduction band edge energy of the n-type contact layer and an electron ground state energy of a quantum well in the set of quantum wells is greater than an energy of a polar optical phonon in a material of the light generating structure; and a set of barriers interlaced with set of quantum wells, the set of barriers including a first barrier immediately adjacent to a first quantum well in the set of quantum wells and the first side of the light generating structure, wherein a thickness of the first barrier is sufficient to accelerate an injected electron in an electric field to reach the energy of the polar optical phonon with respect to the electron ground state energy in the first quantum well, and wherein a thickness of a remainder of the light generating structure exceeds a mean free path for emission of a polar optical phonon by an electron injected into the light generating structure.

Additional aspects of the invention provide methods of designing and/or fabricating the heterostructures and devices shown and described herein, as well as methods of designing and/or fabricating circuits including such devices, and the resulting circuits. The illustrative aspects of the invention are designed to solve one or more of the problems herein described and/or one or more other problems not discussed.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features of the disclosure will be more readily understood from the following detailed description of the various aspects of the invention taken in conjunction with the accompanying drawings that depict various aspects of the invention.

FIG. **1** shows an illustrative band diagram of a deep UV light emitting heterostructure including an energy tub according to a previous solution.

FIG. **2** shows a band diagram of an illustrative light emitting heterostructure according to an embodiment.

FIG. **3** shows a band diagram for an illustrative light emitting heterostructure according to another embodiment.

FIG. **4** shows a band diagram for an illustrative light emitting heterostructure according to yet another embodiment.

FIG. **5** shows a band diagram for an illustrative light emitting heterostructure according to still another embodiment.

FIG. **6** shows an illustrative heterostructure for a light emitting diode according to an embodiment.

FIG. **7** shows reflection coefficients of different coatings for illustrative reflective contacts.

FIGS. **8**A-**8**D show illustrative LED configurations with composite contacts according to embodiments.

FIG. **9** shows a chart comparing illustrative transmission spectra of conventional and transparent 340 nanometer DUV LEDs structures.

FIG. **10** shows a chart illustrating an illustrative performance improvement of a 340 nm DUV LED structure with a reflecting contact.

FIG. **11** shows an illustrative configuration for a flip chip LED according to an embodiment.

FIG. **12** shows a dependence of the absorption coefficient on the wavelength for various aluminum molar fractions (x) of an $Al_xGa_{1-x}N$ alloy according to an embodiment.

FIG. **13** shows an illustrative chart for selecting an aluminum content of an AlGaN alloy to maintain a target transparency for a corresponding emitted wavelength according to an embodiment.

FIG. **14** shows an illustrative flow diagram for fabricating a circuit according to an embodiment.

It is noted that the drawings may not be to scale. The drawings are intended to depict only typical aspects of the invention, and therefore should not be considered as limiting the scope of the invention. In the drawings, like numbering represents like elements between the drawings.

DETAILED DESCRIPTION OF THE INVENTION

As indicated above, aspects of the invention provide a light emitting diode, which includes an n-type contact layer and a light generating structure adjacent to the n-type contact layer. The light generating structure includes a set of quantum wells. The contact layer and light generating structure can be configured so that a difference between an energy of the n-type contact layer and an electron ground state energy of a quantum well is greater than an energy of a polar optical phonon in a material of the light generating structure. Additionally, the light generating structure can be configured so that its width is comparable to a mean free path for emission of a polar optical phonon by an electron injected into the light generating structure. The diode can include a blocking layer, which is configured so that a difference between an energy of the blocking layer and the electron ground state energy of a quantum well is greater than the energy of the polar optical phonon in the material of the light generating structure. The diode can include a composite contact, including an adhesion layer, which is at least partially transparent to light generated by the light generating structure and a reflecting metal layer configured to reflect at least a portion of the light generated by the light generating structure. As used herein, unless otherwise noted, the term “set” means one or more (i.e., at least one) and the phrase “any solution” means any now known or later developed solution. Furthermore, as used herein, it is understood that the term “light” includes electromagnetic radiation of any wavelength, whether within the visible spectrum or outside of the visible spectrum.

Turning to the drawings, FIG. **1** shows an illustrative band diagram of a deep UV light emitting heterostructure **2** including an energy tub **4** according to a previous solution. In particular, a light generating multiple quantum well (MQW) structure **6** of the heterostructure **2** is confined to the energy tub **4**. However, the inventors have found that such a band diagram can be difficult to implement for short wavelength structures, in which the Al molar fraction is very high, e.g., greater than fifty percent.

FIG. **2** shows a band diagram of an illustrative light emitting heterostructure **10** according to an embodiment. In this case, the heterostructure **10** includes a light generating structure **12** and an at least partially transparent (e.g., semi-transparent or transparent) injector cladding layer **14** adjacent to the light generating structure **12**. As illustrated, the light generating structure **12** can include interlaced sets of barriers (higher energy in the band diagram) and quantum wells (lower energy in the band diagram). To this extent, each quantum well in the light generating structure **12** has one or more adjacent barriers and each barrier in the light generating structure **12** has one or more adjacent quantum wells. In heterostructure **10**, an energy difference **16** (e.g., band offset) between an energy of an n-type contact layer **18** and an electron ground state energy level in a quantum well in the light generating structure **12** is slightly larger than the energy of a polar optical phonon, $E_{OPT\text{-}PHONON}$, within a material of the light generating structure **12**. In an embodiment, the energy difference **16** exceeds the energy of the polar optical phonon by approximately thermal energy, which is approximately twenty-six milli-electron Volts (meV) at room temperature.

Furthermore, a total width **13** of the light generating structure **12** can be selected to be comparable to a mean free path for emission of a polar optical phonon by an electron injected into the light generating structure **12**. In an embodiment, the width **13** of the light generating structure **12** is configured to be slightly larger than the mean free path, e.g., exceeding the mean free path by less than approximately ten percent. In an embodiment, the width **13** of the light generating structure exceeds the mean free path by less than approximately five percent. However, it is understood that in other embodiments, the width **13** of the light generating structure can exceed the mean free path for emission of the polar optical phonon by greater than ten percent. The illustrative design of heterostructure **10** can achieve one or more of: enhanced transitions of the injected electrons into multiple quantum wells; confinement of the injected electrons in the quantum wells; and improved uniformity of the electron distribution between the multiple quantum wells.

The various layers of heterostructure **10** can be formed using any appropriate material compositions. In an illustrative embodiment, the layers **12**, **14**, **18** are formed using differing wide band gap semiconductor materials, such as differing group III nitride material compositions. Group III nitride materials comprise one or more group III elements (e.g., boron (B), aluminum (Al), gallium (Ga), and indium (In)) and nitrogen (N), such that $B_WAl_XGa_YIn_ZN$, where $0 \leq W, X, Y, Z \leq 1$, and $W+X+Y+Z=1$. Illustrative group III nitride materials include AlN, GaN, InN, BN, AlGaN, AlInN, AlBN, AlGaInN, AlGaBN, AlInBN, and AlGaInBN with any molar fraction of group III elements. In an embodiment, the materials include any combination of: AlN, GaN, InN, and/or BN alloys.

In an embodiment, cladding layer **14** comprises an at least partially transparent magnesium (Mg)-doped AlGaN/AlGaN short period superlattice structure (SPSL). In another embodiment, the n-type contact layer **18** comprises a cladding layer formed of a short period superlattice, such as an AlGaN SPSL, which is at least partially transparent to radiation generated by the light generating structure **12**.

FIG. **3** shows a band diagram for an illustrative light emitting heterostructure **20** according to another embodiment. In heterostructure **20**, a blocking layer **22** is also included adjacent to the cladding layer **14**. In an embodiment, the blocking layer **22** can comprise a group III nitride material having a graded or modulated aluminum composition along a width of the blocking layer **22**. In another embodiment, the blocking layer **22** can comprise a superlattice structure, which can enable an improved materials quality in the heterostructure **20**. Blocking layer **22** can be configured as an electron blocking layer and/or as a cladding layer using any solution.

FIG. **4** shows a band diagram for an illustrative light emitting heterostructure **30** according to yet another embodiment. In heterostructure **30**, a thickness **32** (as measured in the direction of travel for the electrons) of a first barrier **15** in the light generating structure **12** is selected to be sufficient to accelerate electrons injected into the light generating structure **12** from the n-type contact **18** to reach an energy of a polar optical phonon, $E_{OPT\text{-}PHONON}$, with respect to the energy states in the quantum wells. Furthermore, a thickness **34** of a remainder of the light generating structure **12** can be selected to be comparable to (e.g., slightly exceed) the mean free path for the emission of polar optical phonons by electrons.

FIG. **5** shows a band diagram for an illustrative light emitting heterostructure **40** according to still another embodiment. In heterostructure **40**, an energy difference **44** (e.g., band offset) between an energy of a p-type blocking layer **42** and an electron ground state energy in a quantum well within the light generating structure **12** is slightly larger than the energy of the polar optical phonon, $E_{OPT\text{-}PHONON}$, in the material of the light generating structure **12**. In an embodiment, the energy difference exceeds the energy of the polar optical phonon by approximately thermal energy. Blocking layer **42** can be configured as an electron blocking layer and/or as a cladding layer using any solution.

FIG. **6** shows an illustrative heterostructure **50** for a light emitting diode (LED) according to an embodiment. As illustrated, the heterostructure **50** can include a substrate **52**, an n-type contact **54**, a light generating structure **56**, and a p-type contact **58**. In an embodiment, the substrate **52** and n-type contact **54** are at least partially transparent to the light generated by the light generating structure **56**, thereby enabling extraction of light generated by the light generating structure **56** out of the heterostructure **50** through the transparent substrate **52**. Furthermore, the heterostructure **50** can include a distributed semiconductor heterostructure Bragg reflector (DBR) structure **60** on an opposing side of the light generating structure **56** than a transparent side of the heterostructure **50** (e.g., the transparent substrate **52**). The DBR structure **60** can be configured to reflect additional light generated by the light generating structure **56** out of the transparent substrate **52** than would otherwise be provided. Additionally, the heterostructure **50** can include an electron blocking layer **61** located between the DBR structure **60** and the light generating structure **56**, which can suppress residual electron overflow from the n-type contact **54** to the p-type contact **58** without capture into the light generating structure **56**. The electron blocking layer **61** can be configured to be at least partially transparent to the light generated by the light generating structure **56**.

The various components of the heterostructure **50** can be formed from any suitable materials, such as group III nitride materials as described herein. In an embodiment, the n-type contact **54** is formed of a short period superlattice that is at least partially transparent to radiation generated by the light generating structure **56**, which can provide a higher free hole concentration due to better dopant ionization, better crystal quality, and/or higher optical transmission to the emitted radiation. In a further embodiment, the n-type contact **54** (e.g., the short period superlattice) is formed of group III nitride materials.

It is understood that additional layer(s) and/or structure(s) can be included in heterostructure **50**. For example, the heterostructure **50** can include a reflective layer, a photonic crystal, a mirror, and/or the like. These layer(s) and/or structure(s) can be configured to direct light generated by the light generating structure **56** in a manner that increases an amount of light emitted from heterostructure **50** than would be emitted without the presence of the additional layer(s) and/or structures. Similarly, one or more additional layers can be located between any of the layers shown in FIG. **6**. For example, a buffer layer and/or a second layer can be formed directly on the substrate **52**, and the n-type contact **54** can be formed directly on the second layer.

In an embodiment, a heterostructure can include a light generating structure **56** located between a DBR structure **60** and a reflector, such as a metal reflector. In this case, the DBR structure **60** and the reflector (e.g. a reflective contact) can establish resonant optical field distribution, which can enhance an efficiency of light extraction from the heterostructure. The reflector can be formed of any type of material, which is at least partially reflective of the light generated by the light generating structure **56**. In an embodiment, the material of the reflector is selected according to its reflectivity of a range of ultraviolet light including a wavelength corresponding to the peak wavelength of ultraviolet light emitted by the light generating structure **56**.

To this extent, FIG. **7** shows reflection coefficients of different coatings for illustrative reflective contacts. Illustrative reflective contacts can be formed from, among other things, aluminum, enhanced aluminum, aluminum silicon monoxide, aluminum magnesium fluoride, rhodium, enhanced rhodium, gold, and/or the like. As can be seen in FIG. **7**, rhodium and enhanced rhodium provide good reflectivity within the ultraviolet range of wavelengths, particularly when compared to gold. In particular, enhanced rhodium provides excellent reflectivity in the deep ultraviolet range of wavelengths (e.g., wavelengths below approximately 0.3 micrometers (μm). However, rhodium does not provide good ohmic contact to AlGaN materials.

In an embodiment, a light emitting diode, such as a deep ultraviolet light emitting diode, includes a composite reflecting contact. For example, FIG. **8**A shows an illustrative configuration for an LED **62**, which includes a composite contact **63** comprising a thin (e.g., 2-5 nanometers thick) layer **64** of a first metal adjacent to a layer **66** of rhodium and/or enhanced rhodium. Layer **64** can be formed of any metal, which is at least partially transparent to light generated by a light emitting heterostructure **68** at the corresponding thickness of the layer **64** and which provides improved ohmic contact and/or adhesion of the thicker reflective layer **66** to the surface of the heterostructure **68**, such as a heterostructure formed of group III nitride materials. In an embodiment, layer **64** is formed of nickel (Ni). However, it is understood that layer **64** can be formed of any suitable material, including Nickel oxyhydroxide (NiOx), Palladium (Pd), Molybdenum (Mo), Cobalt (Co), and/or the like.

Various alternative composite contact configurations are possible. For example, FIG. **8**B shows an illustrative configuration for an LED **70** including a composite contact **72** formed of multiple layers of metals **74**A-**74**F (e.g., a metallic superlattice), each of which can be at least partially transparent or reflective of light emitted by a corresponding light emitting heterostructure **76**, such as a heterostructure formed of group-III nitride materials, of the LED **70**. In an embodiment, each of the layers of metals **74**A-**74**F is configured to be at least partially transparent to the light emitted by the light emitting heterostructure **76**. For example, the layers of metals **74**A-**74**F can include alternating thin (e.g., 2-5 nanometers thick) layers of two metals selected from: Ni, NiOx, Pd, Mo, Co, and/or the like, which can be oxidized in an O_2 ambient. Use of the multiple layers of metals **74**A-**74**F can enable improved reflectivity/transparency and/or polarization control of the radiation reflected by/passing through the composite contact **72**. While the composite contact **72** is shown including three repeating sets of two metals each, it is understood that the composite contact **72** can include any combination of two or more metals and any number of layers.

In another embodiment, a composite contact can include graphene. For example, layer **64** of composite contact **63** (FIG. **8**A) and/or a set of layers **74**A-**74**F of composite contact **72** can be formed of graphene, which can be configured to be transparent to light generated by the corresponding heterostructure and very conductive. Another layer, such as layer **66** of composite contact **63** and/or interlaced layers of composite contact **72**, can comprise a thin layer of metal adjacent to the graphene, which can improve current spreading in the composite contact **63**, **72**. In a further embodiment, the composite contact **63**, **73** is at least partially transparent to the light generated by the heterostructure. It is understood that an LED can include one or more layers adjacent to a contact formed of graphene, which are configured to improve light extraction from the LED, e.g., via a textured surface.

Furthermore, a composite contact of the light emitting diode can include one or more non-uniform layers. For example, a non-uniform layer can comprise a varying thickness and/or be absent from certain regions. FIG. **8**C shows an illustrative configuration for an LED **80**, which includes a composite contact **82** formed of a non-uniform transparent adhesion layer **84** and a reflective layer **86**. In an embodiment, the non-uniform transparent adhesion layer **84** comprises nickel, the reflective layer **86** comprises enhanced rhodium, and the light emitting heterostructure **88** comprises a group III nitride heterostructure, which emits ultraviolet radiation, such as deep ultraviolet radiation. In this case, the ultraviolet radiation emitted by the light emitting heterostructure **88** will not be partially absorbed by the transparent adhesion layer **84** in the regions in which it is absent, thereby allowing for direct reflection of the ultraviolet radiation by the reflective layer **86**.

Additionally, the non-uniform distribution of the transparent adhesion layer **84** can result in a non-uniform current, which is mostly limited to the areas where the transparent adhesion layer **84** improves adhesion with the surface of the light emitting heterostructure **88**. As a result, a current density in these regions is higher than that for a uniform adhesion layer, which can thereby enhance radiative recombination. However, the configuration of the non-uniform transparent adhesion layer **84** can be configured to limit the current non-uniformity to a range that will not result in local overheating within the LED **80**, which could result in reliability problems for the LED **80**.

A non-uniform transparent adhesion layer **84** can comprise any type of distribution along the surface of a light emitting heterostructure **88**. For example, FIG. **8**D shows an illustrative configuration for an LED **90**, which includes a composite contact **92** formed of a non-uniform transparent adhesion layer **94** and a reflective layer **96**. In an embodiment, the non-uniform transparent adhesion layer **94** comprises nickel, while the reflective layer **96** comprises enhanced rhodium, and the light emitting heterostructure **88** comprises a group III nitride heterostructure, which emits ultraviolet radiation, such as deep ultraviolet radiation. In this case, the transparent adhesion layer **94** is periodic, thereby forming a reflecting photonic crystal. Formation of the reflecting photonic crystal can improve the light reflection of the composite contact **92**, and therefore the corresponding light extraction of light from the LED **90**.

Sample transparent DUV LEDs were fabricated according to embodiments, along with conventional DUV LEDs for comparison. The DUV LEDs were configured to emit radiation having a peak emission wavelength within or close to the deep ultraviolet range. Each of the transparent DUV LEDs included a transparent Mg-doped AlGaN/AlGaN short period superlattice structure (SPSL) as a cladding layer, which replaced transparent graded p-type AlGaN cladding and p-type GaN contact layers of a typical LED. The DUV LED structures were grown on a sapphire substrate by a combination of metal-organic chemical vapor deposition (MOCVD) and migration enhanced MOCVD. Each of the DUV LEDs included a thin p^{++}-GaN contact layer to create a polarization induced high free hole concentration near the surface and to improve the p-type contact. 300 Kelvin (K) (e.g., room temperature) and 77 K Hall measurements for the DUV LEDs were taken, and indicated free hole concentration of 9.8×10^{17} cm^{-3} and 9.6×10^{17} cm^{-3}, respectively, which is consistent with the formation of a 2-dimensional (2D) hole gas. The measured hole mobility increased from 7.6 $cm^2/V\cdot s$ at 300 K to 11 $cm^2/V\cdot s$ at 77 K.

Optical transmission measurements of the DUV LEDs indicated up to approximately eighty percent transmission at the peak LED emission wavelength for the respective DUV LEDs. Furthermore, the Al-based and Rh-based reflecting contacts provided more than sixty percent reflectivity within the deep ultraviolet range. FIG. **9** shows a chart comparing illustrative transmission spectra of conventional and transparent 340 nanometer DUV LEDs structures.

The forward voltage (V_f) of 340 nm DUV LEDs with conventional Ni/Au p-type contacts and absorbing and transparent p-type cladding layers was measured to be 5.2 Volts (V) and 6.1 V at 20 mA, respectively. Use of a reflecting p-type contact resulted in an additional approximately 0.1-0.2 V increase of V_f due to the voltage drop across the contact barrier. For shorter emission wavelengths, the voltage drop across SPSL caused an increase in V_f from 5.3 V to 6.4 V. The output power of transparent structure 330-340 nm emission LEDs with conventional and reflecting p-contacts were measured to be 0.83 mW and 0.91 mW at 20 mA, respectively. Devices from the reference wafer showed 0.36 mW at the same current. Testing of 310 nm DUV LEDs before packaging showed a similar increase in the DUV LED efficiency. To this extent, FIG. **10** shows a chart illustrating an illustrative performance improvement of a 340 nm DUV LED structure with a reflecting contact.

The heterostructure and/or contact designs described herein can be utilized in the formation of a device using a flip chip configuration. For example, FIG. **11** shows an illustrative configuration for a flip chip LED **100** according to an embodiment. In an embodiment, LED **100** can comprise a deep ultraviolet LED, which is configured to emit radiation in the deep ultraviolet range of wavelengths. LED **100** can include a mount **102**, which is attached to a device heterostructure **104** using a set of bonding pads **106** and a set of solder bumps **108**.

In an embodiment, the mount **102** is configured to provide protection for the heterostructure **104** from transient voltage surges, such as those caused by electrostatic discharge (ESD), an electric power surge, and/or the like. In a more particular embodiment, the mount **102** is formed of a slightly conductive material, which provides a parallel leakage path for the device heterostructure **104**. For example, the conductive material can comprise a semi-insulating silicon carbide (SiC), which can comprise any of various polytypes of SiC, such as 4H-SiC, 6H-SiC, 3C-SiC, high purity SiC, and/or the like. However, it is understood that the mount **102** can comprise other types of conductive materials and/or ESD protective configurations.

As illustrated, the device heterostructure **104** can include, for example, a reflecting contact **110**, a transparent adhesion layer **112** (which can be uniform or non-uniform as described herein), a p-type contact **114**, a blocking layer **116**, a light generating structure **118**, and a n-type contact **120**. Each of the components of the heterostructure **104** can be fabricated as described herein. During operation of the LED **100**, the reflecting contact **110** can reflect light, such as ultraviolet light, emitted by the light generating structure **118** towards the n-type contact **120**. The n-type contact **120** can be at least partially transparent to the light, thereby emitting the light from the LED **100**. In an embodiment, the n-type contact **120** can comprise a textured surface **122**, which is configured to improve extraction of the light from the LED **100**.

The various heterostructures shown and described herein can be implemented as part of various types of devices, such as a light emitting diode (LED), a superluminescent diode, a laser, and/or the like. In an embodiment, the device is configured to emit ultraviolet radiation during operation (e.g., an ultraviolet LED, an ultraviolet superluminescent LED, and/or the like). In a more particular embodiment, the ultraviolet radiation comprises deep ultraviolet radiation, e.g., 210 nm to 365 nm.

As used herein, a layer is at least partially transparent when the layer allows at least a portion of light in a corresponding range of radiation wavelengths to pass there through. For example, a layer can be configured to be at least partially transparent to a range of radiation wavelengths corresponding to a peak emission wavelength for the light (such as ultraviolet light or deep ultraviolet light) emitted by a light generating structure described herein (e.g., peak emission wavelength +/− five nanometers). As used herein, a layer is at least partially transparent to radiation if it allows more than approximately 0.001 percent of the radiation to pass there through. In a more particular embodiment, an at least partially transparent layer is configured to allow more than approximately five percent of the radiation to pass there through. Similarly, a layer is at least partially reflective when the layer reflects at least a portion of the relevant light (e.g., light having wavelengths close to the peak emission of the light generating structure). In an embodiment, an at least partially reflective layer is configured to reflect more than approximately five percent of the radiation.

In an embodiment, a structure described herein can include one or more layers having a composition selected such that the layer has a transparency of at least a target transparency to radiation, such as ultraviolet radiation, of a target set of wavelengths. For example, a layer can be a group III nitride-based layer, such as an electron blocking layer or a p-type contact layer described herein, which is composed of $Al_xGa_{1-x}N$ where the aluminum molar fraction (x) is sufficiently high in some domains of the layer to result in the layer being at least partially transparent to ultraviolet radiation. In an embodiment, the layer can comprise a superlattice layer located in an emitting device configured to emit radiation having a dominant wavelength in the ultraviolet spectrum, and the composition of at least one sublayer in each period of the superlattice layer is configured to be at least partially transparent to ultraviolet radiation having a target wavelength corresponding to the ultraviolet radiation emitted by the emitting device.

An amount of transparency of a short period superlattice (SPSL) can be approximated by computing an averaged band gap of the SPSL, and deducing average absorption coefficients of the SPSL. The absorption coefficients depend on an absorption edge of the semiconductor material, which for materials formed of an AlGaN alloy, is a function of the molar fractions of the $Al_xGa_{1-x}N$ semiconductor alloy.

In an embodiment, the target transparency for the material is at least ten times more transparent than the least transparent layer of material in the structure (e.g., GaN for a group III nitride-based device). In this case, an absorption coefficient of the semiconductor layer can be on the order of 10^4 inverse centimeters or lower. In this case, a one micron thick semiconductor layer will allow approximately thirty-six percent of the ultraviolet radiation to pass there through.

FIG. **12** shows a dependence of the absorption coefficient on the wavelength for various aluminum molar fractions (x) of an $Al_xGa_{1-x}N$ alloy according to an embodiment. In order to maintain an absorption coefficient of the semiconductor layer at orders of 10^4 inverse centimeters or lower, the content of aluminum in an SPSL barrier layer can be chosen based on the corresponding target wavelength or range of wavelengths. For example, for a target wavelength of approximately 250 nanometers, the aluminum molar fraction can be approximately 0.7 or higher, whereas for a target wavelength of approximately 300 nanometers, the aluminum molar fraction can be as low as approximately 0.4. FIG. **13** shows an illustrative chart for selecting an aluminum content of an $Al_xGa_{1-x}N$ alloy to maintain a target transparency for a corresponding emitted wavelength, λ, according to an embodiment. In this case, the target transparency corresponds to an absorption coefficient of the semiconductor layer on the order of 10^4 inverse centimeters. Note that in FIG. **13**, the dependence of $x=x(\lambda)$ is linear, with $x=C\cdot\lambda+B$, where $C=-0.0048$ [1/nm], and $B=1.83$.

In an embodiment, a device can include one or more layers with lateral regions configured to facilitate the transmission of radiation through the layer and lateral regions configured to facilitate current flow through the layer. For example, the layer can be a short period superlattice, which includes barriers alternating with wells. In this case, the barriers can include both transparent regions, which are configured to reduce an amount of radiation that is absorbed in the layer, and higher conductive regions, which are configured to keep the voltage drop across the layer within a desired range. As used herein, the term lateral means the plane of the layer that is substantially parallel with the surface of the layer adjacent to another layer of the device. As described herein, the lateral cross section of the layer can include a set of transparent regions, which correspond to those regions having a relatively high aluminum content, and a set of higher conductive regions, which correspond to those regions having a relatively low aluminum content.

The set of transparent regions can be configured to allow a significant amount of the radiation to pass through the layer, while the set of higher conductive regions can be configured to keep the voltage drop across the layer within a desired range (e.g., less than ten percent of a total voltage drop across the structure). In an embodiment, the set of transparent regions occupy at least ten percent of the lateral area of the layer, while the set of higher conductive regions occupy at least approximately two percent (five percent in a more specific embodiment) of the lateral area of the layer. Furthermore, in an embodiment, a band gap of the higher conductive regions is at least five percent smaller than the band gap of the transparent regions. In a more particular embodiment, the transparent regions comprise a transmission coefficient for radiation of a target wavelength higher than approximately sixty percent (eighty percent in a still more particular embodiment), while the higher conductive regions have a resistance per unit area to vertical current flow that is smaller than approximately 10^{-2} ohm·cm^2. As used herein, the term transmission coefficient means the ratio of an amount of radiation exiting the region to an amount of radiation entering the region.

The transparent and conductive regions can be formed using any solution. For example, a layer can be grown using migration-enhanced metalorganic chemical vapor deposition (MEMOCVD). During the growth, inhomogeneities in the lateral direction of a molar fraction of one or more elements, such as aluminum, gallium, indium, boron, and/or the like, can be allowed in the layer. In an embodiment, such compositional inhomogeneities can vary by at least one percent.

While shown and described herein as a method of designing and/or fabricating a structure and/or a corresponding semiconductor device including the structure, it is understood that aspects of the invention further provide various alternative embodiments. For example, in one embodiment, the invention provides a method of designing and/or fabricating a circuit that includes one or more of the devices designed and fabricated as described herein.

To this extent, FIG. **14** shows an illustrative flow diagram for fabricating a circuit **146** according to an embodiment. Initially, a user can utilize a device design system **130** to generate a device design **132** using a method described herein. The device design **132** can comprise program code, which can be used by a device fabrication system **134** to generate a set of physical devices **136** according to the features defined by the device design **132**. Similarly, the device design **132** can be provided to a circuit design system **140** (e.g., as an available component for use in circuits), which a user can utilize to generate a circuit design **142** (e.g., by connecting one or more inputs and outputs to various devices included in a circuit). The circuit design **142** can comprise program code that includes a device designed using a method described herein. In any event, the circuit design **142** and/or one or more physical devices **136** can be provided to a circuit fabrication system **144**, which can generate a physical circuit **146** according to the circuit design **142**. The physical circuit **146** can include one or more devices **136** designed using a method described herein.

In another embodiment, the invention provides a device design system **130** for designing and/or a device fabrication system **134** for fabricating a semiconductor device **136** using a method described herein. In this case, the system **130**, **134** can comprise a general purpose computing device, which is programmed to implement a method of designing and/or fabricating the semiconductor device **136** as described herein. Similarly, an embodiment of the invention provides a circuit design system **140** for designing and/or a circuit fabrication system **144** for fabricating a circuit **146** that includes at least one device **136** designed and/or fabricated using a method described herein. In this case, the system **140**, **144** can comprise a general purpose computing device, which is programmed to implement a method of designing and/or fabricating the circuit **146** including at least one semiconductor device **136** as described herein.

The foregoing description of various aspects of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed, and obviously, many modifications and variations are possible. Such modifications and variations that may be apparent to an individual in the art are included within the scope of the invention as defined by the accompanying claims.

What is claimed is:

1. A light emitting heterostructure comprising:

an n-type contact layer formed of a group III nitride material; and

a light generating structure adjacent to the n-type contact layer, the light generating structure formed within a group III nitride material having an aluminum molar fraction greater than fifty percent and forming a conduction band energy tub with respect to the n-type contact layer and including a plurality of quantum wells, wherein a difference between a conduction band edge energy of the n-type contact layer and an electron ground state energy of a quantum well in the plurality of quantum wells is greater than an energy of a polar optical phonon in a material of the light generating structure, and wherein a width of the light generating structure is comparable to a mean free path for emission of a polar optical phonon by an electron injected into the material forming the conduction band energy tub.

2. The heterostructure of claim **1**, wherein the width of the light generating structure exceeds the mean free path for emission of a polar optical phonon by an electron injected into the material forming the conduction band energy tub by less than approximately ten percent, and wherein the difference exceeds the energy of the polar optical phonon by approximately thermal energy.

3. The heterostructure of claim **1**, further comprising a blocking layer located on an opposite side of the light generating structure as the n-type contact layer, wherein a difference between a conduction band edge energy of the blocking layer and the electron ground state energy of a quantum well in the plurality of quantum wells is greater than the energy of a polar optical phonon in the material of the light generating structure.

4. The heterostructure of claim **1**, wherein the light generating structure further includes a set of barriers alternating with the plurality of quantum wells, the set of barriers including a first barrier immediately adjacent to a first quantum well in the plurality of quantum wells and the n-type contact layer, wherein a thickness of the first barrier is sufficient to accelerate an injected electron in an electric field to reach the energy of the polar optical phonon with respect to the electron ground state energy in the first quantum well, and wherein a thickness of a remainder of the light generating structure exceeds the mean free path for emission of the polar optical phonon.

5. The heterostructure of claim **1**, further comprising:

an at least partially transparent substrate, wherein the n-type contact is located between the substrate and the light generating structure, and wherein the at least partially transparent substrate and the n-type contact layer are at least partially transparent to the light generated by the light generating structure; and

a Bragg reflector structure formed on an opposite side of the light generating structure as the n-type contact, wherein the Bragg reflector structure is configured to reflect light generated by the light generating structure towards the substrate.

6. The heterostructure of claim **5**, further comprising an electron blocking layer formed between the light generating structure and the Bragg reflector structure.

7. The heterostructure of claim **5**, wherein the n-type contact comprises a short period superlattice.

8. The heterostructure of claim **1**, further comprising a composite contact located on an opposite side of the light generating structure as the n-type contact layer, the composite contact comprising:

an adhesion layer, wherein the adhesion layer is at least partially transparent to light generated by the light generating structure; and

a reflecting metal layer configured to reflect at least a portion of the light generated by the light generating structure.

9. The heterostructure of claim **8**, wherein the adhesion layer comprises a thin layer of one of: nickel, palladium, molybdenum, or cobalt, and wherein the reflecting metal layer comprises one of: aluminum, enhanced aluminum, rhodium, or enhanced rhodium.

10. The heterostructure of claim **8**, wherein the adhesion layer comprises a non-uniform layer.

11. The heterostructure of claim **10**, wherein the non-uniform adhesion layer is configured to form a photonic crystal.

12. The heterostructure of claim **8**, further comprising a distributed semiconductor heterostructure Bragg reflector (DBR) structure, wherein the DBR structure is located on an opposite side of the light generating structure as the composite contact.

13. The heterostructure of claim **1**, further comprising a composite contact located on an opposite side of the light generating structure as the n-type contact layer, wherein at least one layer of the composite contact is formed of graphene.

14. The heterostructure of claim **1**, further comprising a metallic superlattice contact located on an opposite side of the light generating structure as the n-type contact layer, wherein the metallic superlattice includes a plurality of intertwined layers of a first metal and a second metal distinct from the first metal, and wherein the metallic superlattice is at least partially transparent to light generated by the light generating structure.

15. A light emitting heterostructure comprising:

an n-type contact layer; and

a light generating structure adjacent to the n-type contact layer, the light generating structure formed within a material forming a conduction band energy tub with respect to the n-type contact layer and including a plurality of quantum wells, wherein a width of the light generating structure is comparable to a mean free path for emission of a polar optical phonon by an electron injected into the material forming the conduction band energy tub; and

a blocking layer located on an opposite side of the light generating structure as the n-type contact layer, wherein a difference between a conduction band edge energy of the blocking layer and an electron ground state energy of a quantum well in the plurality of quantum wells is greater than an energy of a polar optical phonon in a material of the material forming the conduction band energy tub.

16. The heterostructure of claim **15**, wherein the width of the light generating structure exceeds the mean free path for emission of a polar optical phonon by an electron injected into the material forming the conduction band energy tub by less than approximately ten percent.

17. The heterostructure of claim **15**, wherein the n-type contact layer is formed of a group III nitride material, and wherein the material forming the conduction band energy tub is a group III nitride material having an aluminum molar fraction greater than fifty percent.

18. The heterostructure of claim **15**, wherein the light generating structure further includes a set of barriers alternating with the plurality of quantum wells, the set of barriers including a first barrier immediately adjacent to a first quantum well in the plurality of quantum wells and the n-type contact layer, wherein a thickness of the first barrier is sufficient to accelerate an injected electron in an electric field to reach the energy of the polar optical phonon with respect to the electron ground state energy in the first quantum well, and wherein a thickness of a remainder of the light generating structure exceeds the mean free path for emission of the polar optical phonon.

19. A light emitting device comprising:

an n-type contact layer;

a light generating structure adjacent to the n-type contact layer, wherein the light generating structure is formed within a material forming a conduction band energy tub with respect to the n-type contact layer, the light generating structure including:

a set of quantum wells, wherein a difference between a conduction band edge energy of the n-type contact layer and an electron ground state energy of a quantum well in the set of quantum wells is greater than an energy of a polar optical phonon in the material forming the conduction band energy tub; and

a set of barriers alternating with set of quantum wells, the set of barriers including a first barrier immediately adjacent to a first quantum well in the set of quantum wells and the first side of the light generating structure, wherein a thickness of the first barrier is sufficient to accelerate an injected electron in an electric field to reach the energy of the polar optical phonon with respect to the electron ground state energy in the first quantum well, and wherein a thickness of a remainder of the light generating structure exceeds a mean free path for emission of a polar optical phonon by an electron injected into the material forming the conduction band energy tub; and

a composite contact located on an opposite side of the light generating structure as the n-type contact layer, the composite contact comprising:

an adhesion layer, wherein a material forming the adhesion layer has a maximum thickness less than five nanometers and allows at least five percent of the light generated by the light generating structure to pass there through; and

a reflecting metal layer configured to reflect at least a portion of the light generated by the light generating structure.

20. The device of claim 19, wherein the n-type contact layer is formed of a group III nitride material, and wherein the material forming the conduction band energy tub is a group III nitride material having an aluminum molar fraction greater than fifty percent.

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